The effect of melt on the seismic anisotropy of ice polycrystalline aggregates

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INTRODUCTION

- Observations of P-wave (Vp) and S-wave (Vs) velocities in ice sheets reveal a strong decrease of ~25% of Vs with depth, while Vp remains approximately constant
- The low Vs may be due to the presence of unfrozen liquids resulting from pre-melting at grain joints and/or melting of chemical solutions buried in ice (Wittlinger and Farra, 2015)

Although previous studies of two-phase rocks (including melt and water) show that seismic velocities depend on both CPO and water content, studies on **the effect of melt on polar ice seismic velocity are scarce**

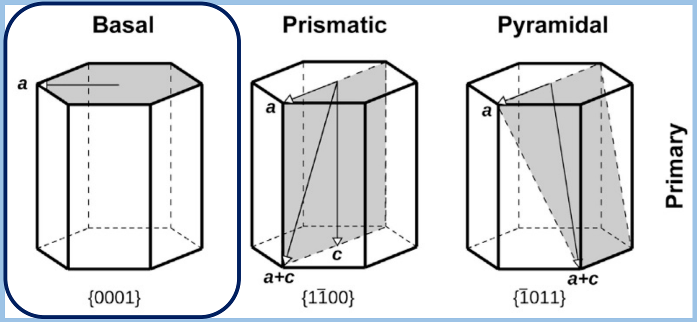
Aim → Analyse polycrystalline ice with different melt fractions (temperate ice) through numerical simulations to:

- Understand how melt influences the development of microstructures
- Link the developed microstructures to the changes in P- and faster S-wave velocities during ice deformation

Ice deformation mechanisms and rheology

Ice is **highly anisotropic**: the critical resolved shear stress required to activate slip systems (CRSS) for non basal vs basal slip systems is A>60

Deformation is mainly accommodated by **dislocation creep.** Preferential glide on the **basal plane** and along the <1120> direction



Hondoh (2000)

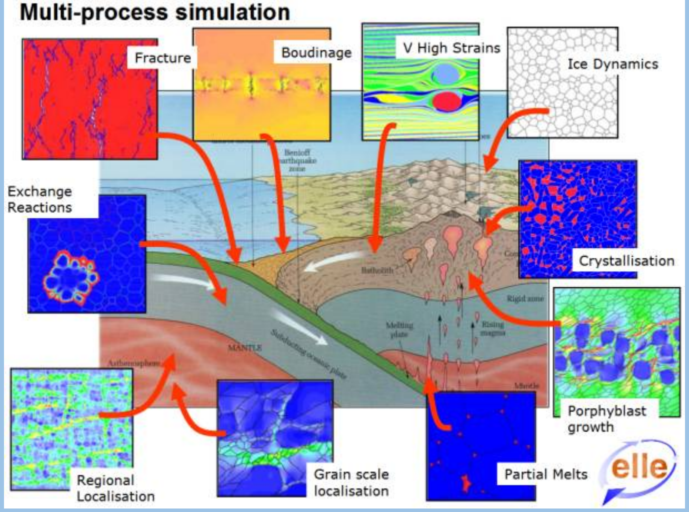
Viscoplastic deformation increases dislocation density and produces an **increment of the internal strain energy**. It can be reduced by:

- Recovery (annihilation of opposite dislocations and poligonisation)
- Recrystallisation (reduction of boundary energy and dislocation density)

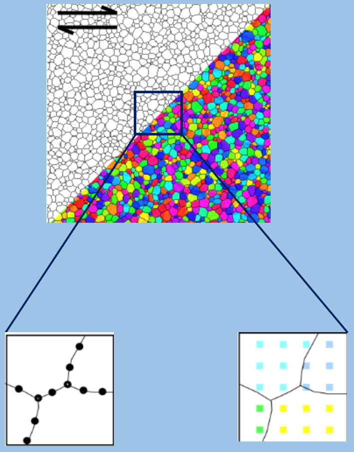
Objective and Simulation Approach

Objective: Simulate temperate ice deformation in simple shear using VPFFT (Full Field crystal plasticity code) + dynamic recrystallisation (*DRX*) processes (recovery, recrystallisation and polygonisation) in order to investigate the **evolution of the microstructure and seismic velocity anisotropy during deformation**

Simulation approach: ELLE is an open-source numerical simulation platform used to simulate the development of microstructures during tectonic and/or metamorphic processes.

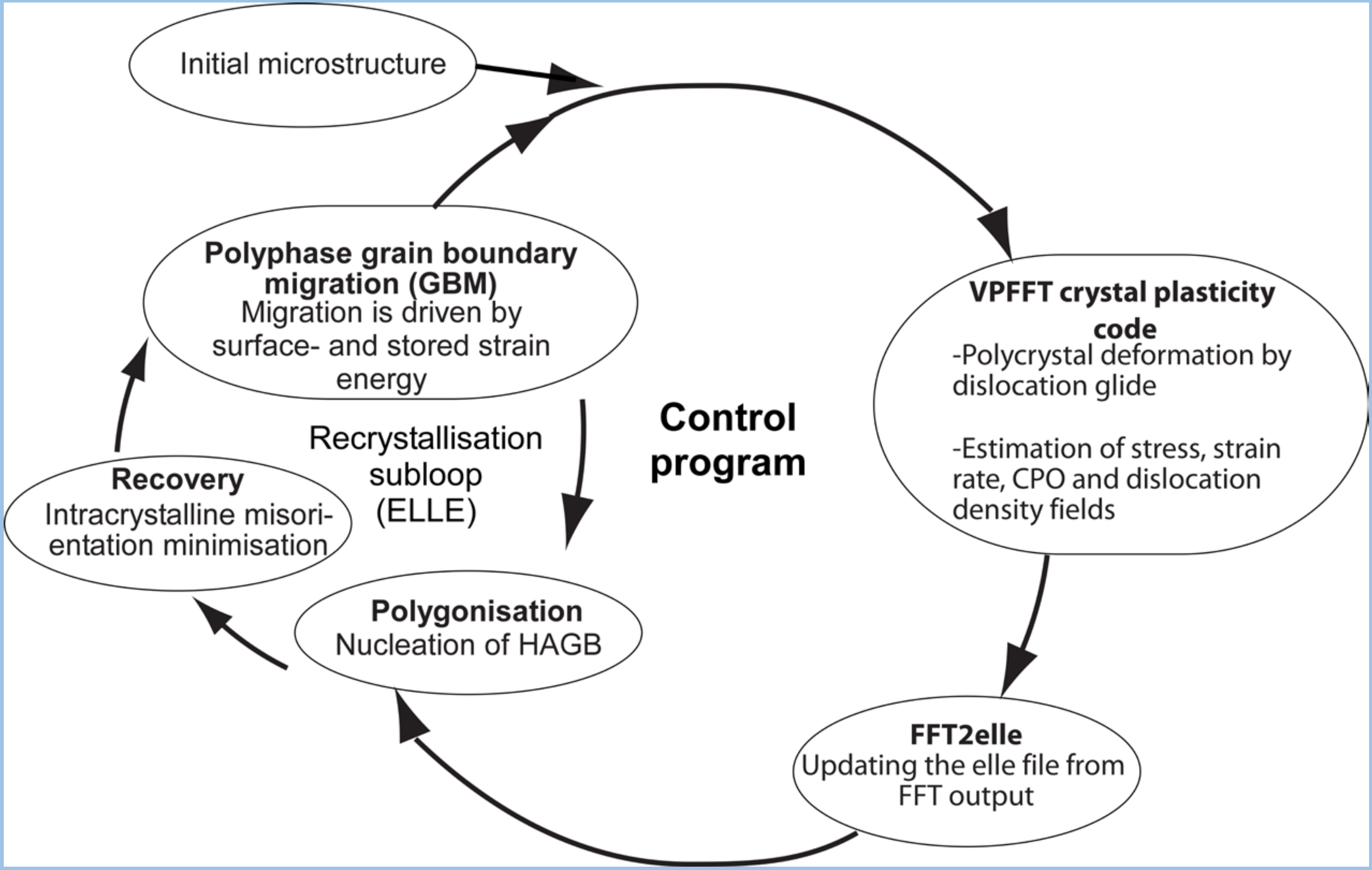


ELLE data layers: the initial microstructure in simple shear simulations is a square model (*L*x*L*)

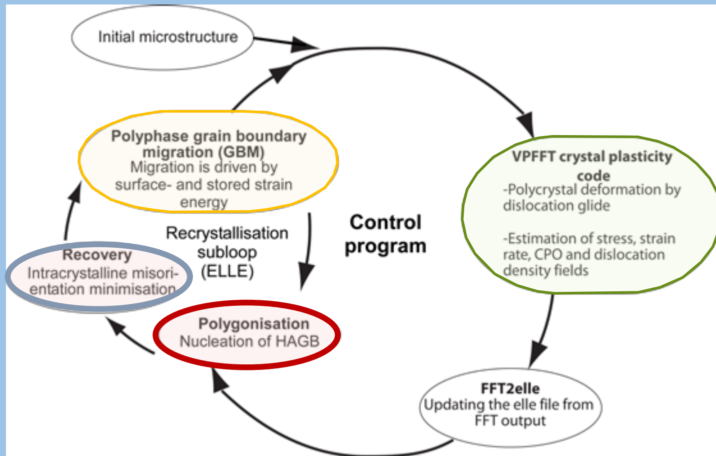


Objective and Simulation Approach

VPFFT (Viscoplastic full-field algorithm) solves the mechanical problem by finding the strain rate and stress field that minimize the average local work-rate. Viscoplastic deformation is accommodated by **dislocation glide**

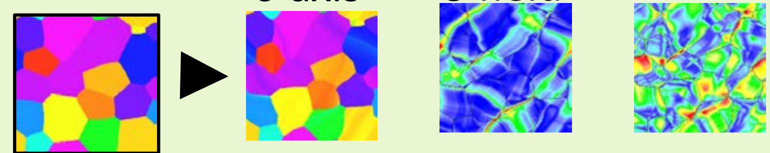


OBJECTIVE AND SIMULATION APPROACH



VPFFT (Viscoplastic full-field algorithm) (Lebensohn, 2001)

$$\dot{\varepsilon}(x) = \dot{\gamma}_0 \sum_s m^s(x) \left(\frac{m^s(x) : \sigma'(x)}{\tau_0^s(x)} \right)^n$$

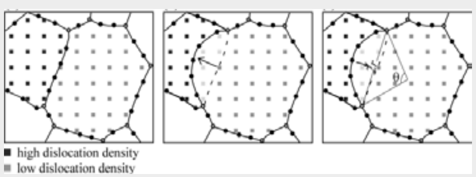


Griera et al. (2011)

Recovery

Reduction internal misorientation

Polyphase GBM

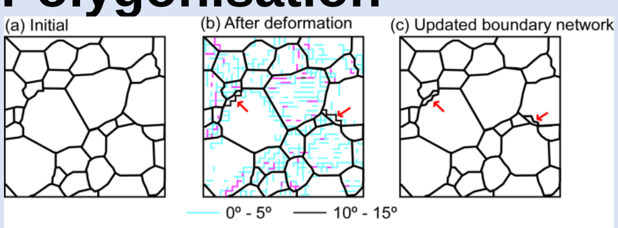


Reduction of the boundary energy

Reduction of the dislocation density

Steinbach et al. (2016); Llorens et al. (2019)

Polygonisation

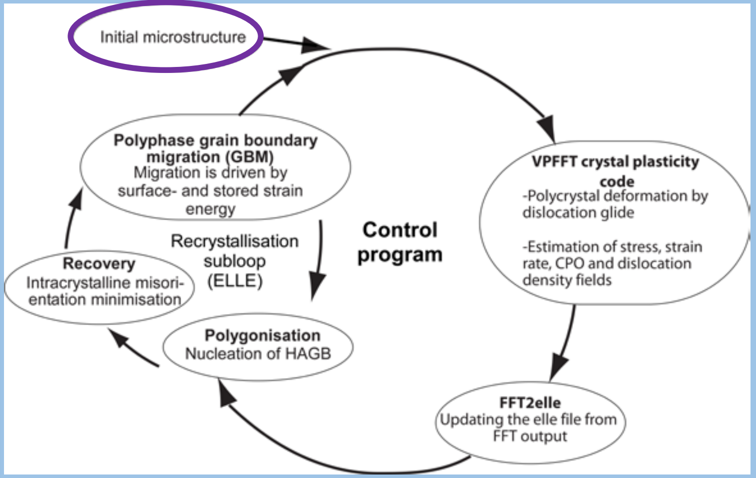


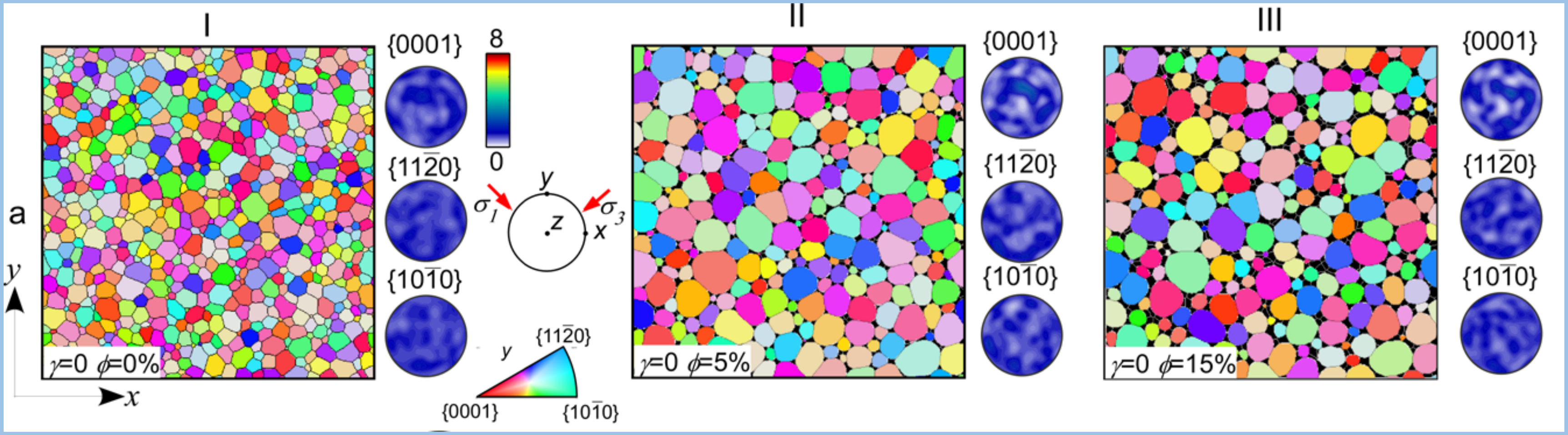
Identifies the high angle grain boundaries (HAGB) and updates the grain boundary network

Llorens et al. (2017)

OBJECTIVE AND SIMULATION APPROACH

- Ice with 3 different melt fractions of 0%, 5% and 15% located at triple grain junctions
- Initial random distribution of c-axis orientation (bulk isotropic)
- Ice: A=60 (CRSS basal vs non-basal slip systems) and n=3 and melt A=1 and n=3
- Dextral simple shear increments of 0.02 shear strain up to 8
- Dynamic recrystallisation applied in a sub-step sequence repeated 10 times after deformation

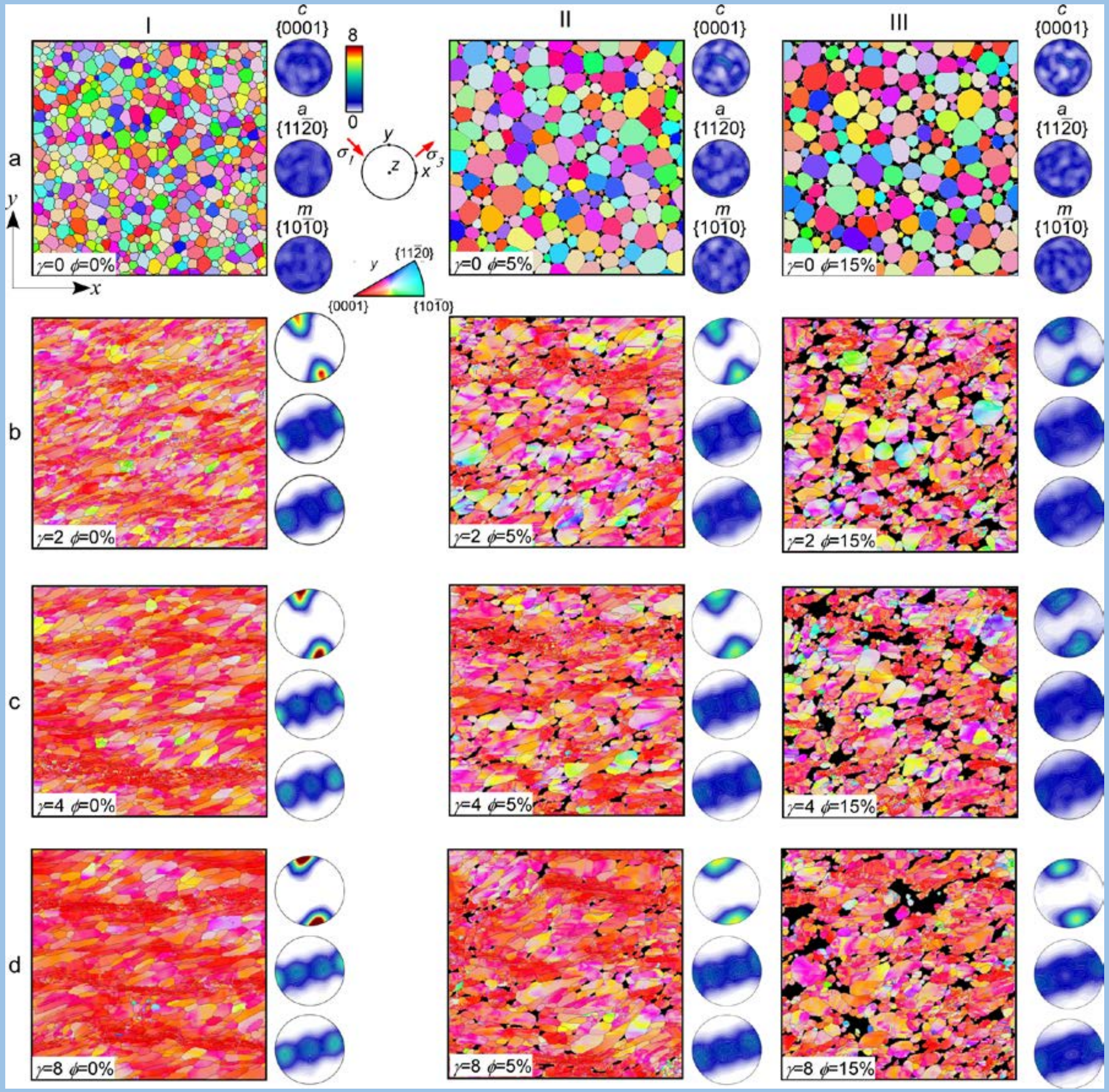




Crystal Preferred Orientation evolution

EXPERIMENTAL RESULTS

no melt (ϕ=0%) with melt (ϕ=5%) with melt (ϕ=15%)



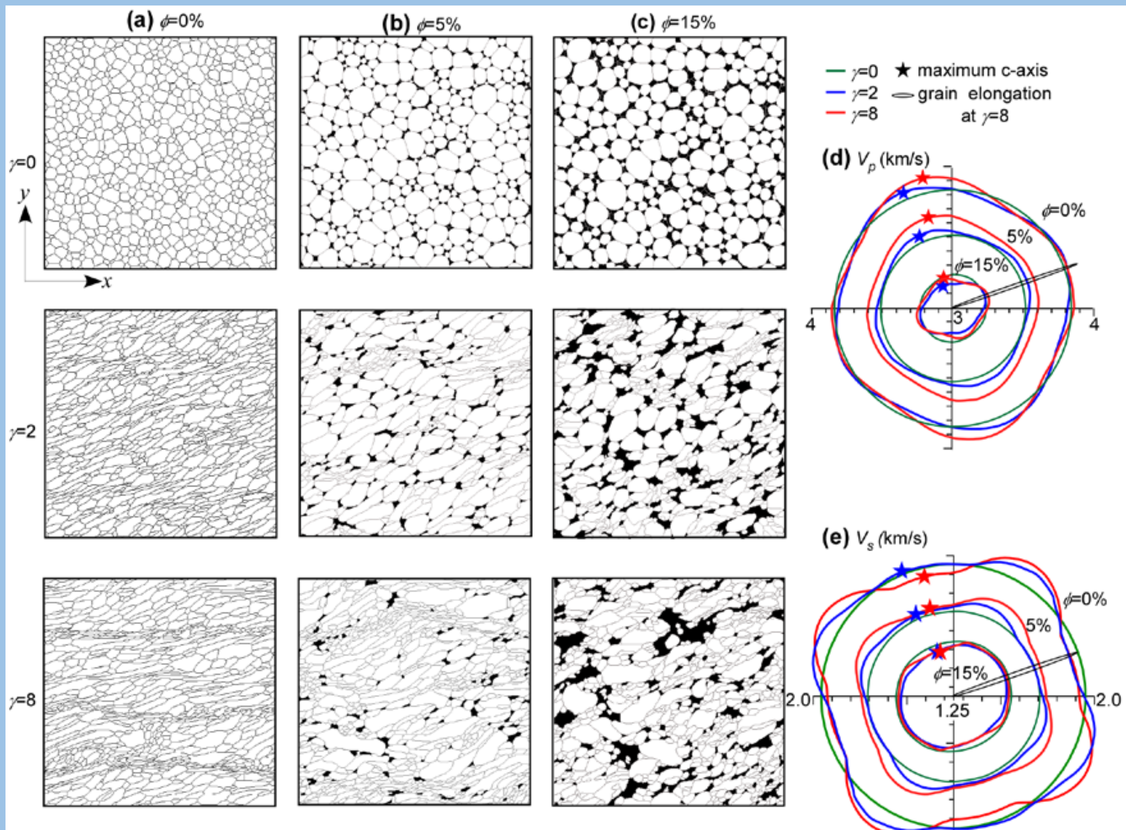
- Regardless the melt percentage (ϕ), all simulations evolve from a random fabric to a c-axis preferred orientation (CPO) approximately perpendicular to the shear plane.
- When melt is present (columns II and III), the developed CPO is less intense than the pure ice simulation (I)

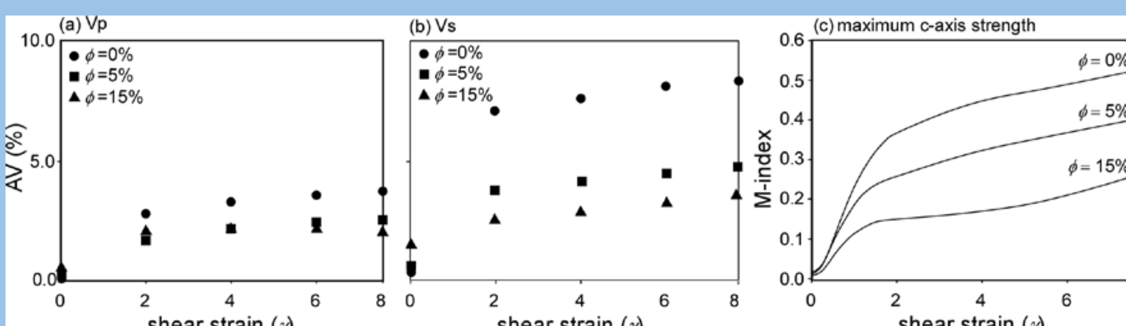
Calculation of P-wave and S-wave velocities

Using the AEH-EBSD Analysis Toolbox (Vel et al., 2016)

EXPERIMENTAL RESULTS

no melt 5% melt 15% melt





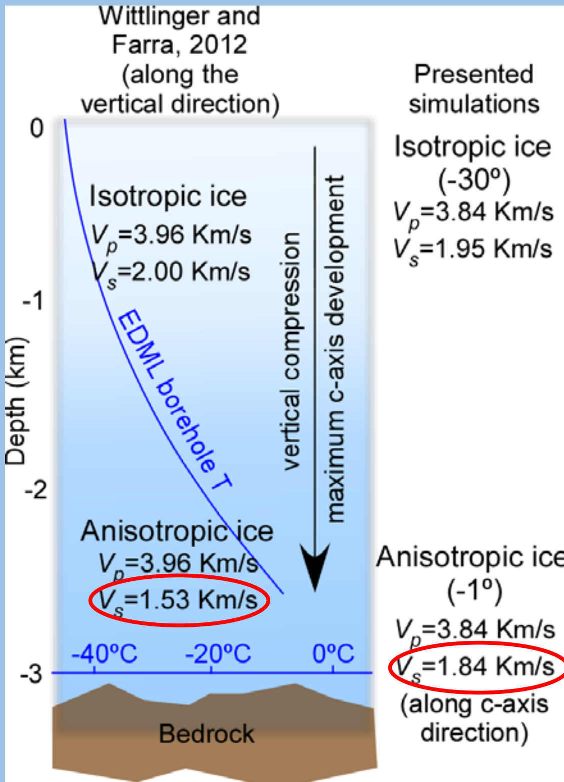
For zero melt (ϕ=0%), the highest Vp quickly aligns with the maximum c-axis orientation. At the same time, the maximum c-axis development reduces Vs in this orientation

When water is present (ϕ>0%) the developed maximum c-axis is less intense, which results in both Vp and Vs being lower than in the case of purely solid ice. At high percentage of water (ϕ=15%), Vp is not aligned with the maximum c-axis, but follow the orientation of the grain elongation

For all simulations the anisotropy of Vp and Vs increases up to γ=2. Higher anisotropies are observed in S-wave velocities. When water in present, the anisotropy of both Vp and Vs is reduced, as the developed maximum c-axis is less intense

EXPERIMENTAL RESULTS

Calculation of P-wave and S-wave velocities



The temperature dependence of the ice elastic parameters, together with the increment of Vp and decrease of Vs along the c-axis direction is due to the CPO development, but cannot explain itself the strong decrease of 25% in the Vs in the lower part of the ice-sheets

The presence of unfrozen liquids has been proposed as the cause of the low Vs found in the lower ice layer. But, even if melting occurs in a microstructure with a strong CPO, **Vp would get proportionally reduced by the presence of water (Table 1)**

Ice conditions	Tº			
		V_p	V_s	V_p /V_s
Purely-solid isotropic ice (standard)	-30ºC	3.84	1.95	1.97
Purely-solid anisotropic ice	-1ºC	3.84	1.84	2.07
Anisotropic ice + 5% water	-1ºC	3.70	1.77	2.10
Anisotropic ice + 10% water	-1ºC	3.51	1.67	2.10
Anisotropic ice + 15% water	-1ºC	3.30	1.53	2.16

Table 1. Predicted Vp and Vs assuming the water bulk modulus for the melt phase.

EXPERIMENTAL RESULTS

Calculation of P-wave and S-wave velocities

Ice conditions	Tº			
		V_p	V_s	V_p / V_s
Purely-solid isotropic ice (standard)	-30ºC	-	-	-
Purely-solid anisotropic ice	-1ºC	-	-	-
Anisotropic ice + 5% water	-1ºC	3.84	1.77	2.17
Anisotropic ice + 10% water	-1ºC	3.83	1.66	2.31
Anisotropic ice + 15% water	-1ºC	3.80	1.54	2.46

Table 2. Predicted Vp and Vs assuming ice bulk modulus at -1ºC for both ice and melt phase.

The presented simulations are located at the transition between the deformation- and the recrystallisation-controlled regime, where **water is located in isolated pockets and not forming water pocket networks**. At this undrained conditions the bulk modulus of the water and ice aggregate must tend to the ice bulk modulus. **If we assume this condition, Vs is significantly reduced proportionally to the presence of water, while Vp is only slightly reduced (Table 2).** That would correspond to a thermomechanical regime of warm-based ice-sheet but with a thin temperate layer, where most of the deformation is internal and can be described by a standard power law flow law.

However, if we consider that the dynamic conditions in the lower part of the ice sheets correspond to the deformation-dominated regime, recrystallisation is too slow to counteract the shearing of water pockets and pockets get stretched continuously. **Melt films located on grain boundaries will modify and even overprint the CPO-dependent orientation and magnitude seismic anisotropy.**